A Cat's Eye Multiple Quantum Well Modulating Retro-reflector

W. S. Rabinovich, R. Mahon, P. Goetz., E. Waluschka, D.. S. Katzer, S. Binari and G. C. Gilbreath

***Abstract*—A new kind of modulating retro-reflector using cat's eye optics and a multiple quantum well electro-absorption modulator array is described. The device exhibits retro-reflection over a 30degree field of view and can support data rates of up to 50 Mbps using 1 mm pixels. The use of the device in free space optical communication is discussed.**

***Index Terms*--).**

I. Introduction

Modulating retro-reflectors (MRR) couple passive optical retro-reflectors with electro-optic shutters to allow free-space optical communication with a laser and pointing/acquisition/tracking system required on only one end of the link. In operation a conventional free space optical communications terminal[1], the interrogator, is used on one end of the link to illuminate the MRR on the other end of the link with a cw beam. The MRR imposes a modulation on the interrogating beam and passively retro-reflects it back to the interrogator. These types of systems are attractive for asymmetric communication links for which one end of the link cannot afford the weight, power and expense of a conventional free-space optical communication terminal. The MRR demonstrated to date have used a large area modulator placed in front of the aperture, or as one of the faces, of a corner-cube retro-reflector. MRR based on ferro-electric liquid crystals[2], MEMS devices[3] and multiple quantum well (MQW) electro-absorption modulators[4] have been demonstrated recently.

For both the liquid crystal and MEMS devices the maximum modulation rate is set by the intrinsic switching speed of the material, which are tens of KHz and hundreds of KHz respectively. For the MQW MRR however, the maximum modulation can range into the gigahertz, limited only by the RC time constant of the device. This limitation, however, is a serious one. The optical aperture of an MRR cannot be too small or the amount of light retro-reflected will be insufficient to close the link. For typical MQW MRR devices the modulator has a diameter between 0.5-1 cm and maximum modulation rates less than 10 MHz. This size device is sufficient to close a link at this rate at ranges over ten kilometers, depending on atmospheric conditions and the interrogator. In this letter we describe a new kind of MQW MRR in which much higher modulation rates can be achieved using small MQW modulators simultaneously with large optical apertures.

II. Scaling rules for modulating retro-reflectors

The optical signal returned by an MRR scales as

$$\frac{P_{laser} \cdot D_{retro}{}^{4} \cdot D_{rec}{}^{2}}{\theta_{div}{}^{2} \cdot R^{4}} \cdot \left(1 - \frac{1}{N_{ext}}\right) e^{-2\alpha_{\mathrm{mod}} L_{\mathrm{mod}}} e^{-2\alpha_{atm} R} \tag{1}$$

where P_{laser} is the power in the interrogating laser, D_{retro} is the optical aperture of the retro-reflector, D_{rec} is the diameter of the interrogator's receive telescope, θ_{div} is the divergence of the outgoing beam from the interrogator, R is the range, N_{ext} is the extinction ratio of the modulator , α_{mod} is the absorption in the modulator , L_{mod} is the thickness of the modulator and α_{atm} is the absorption or scattering loss in the atmosphere.

When atmospheric attenuation is not severe, an MRR link is dominated by the two fourth power relations in (1). The link drops off with range as $1/R^4$. The optical signal, however, increases as the fourth power of the retro-reflector diameter. This obviously motivates using larger retro-reflectors. However for an MQW modulator the capacitance is proportional to the area of the modulator and so the maximum modulation rate scales as

$$1/R_{mod}D_{mod}{}^{2}, \tag{2}$$

where R_{mod} is the sheet resistance and D_{mod} the diameter of the MQW. For a typical MQW modulator capacitances are about 5 nF/cm^2 and sheet resistances vary between 10 and 100 Ohms. Thus the RC modulation limit for an MQW modulator is from 1-20 MHz/cm^2.

This problem can be circumvented by pixellating the modulator into smaller segments and driving those segments with the same signal. This approach however does not reduce the power consumption of the modulator which scales as

$$D_{mod}{}^{2}V^{2}f \tag{3}$$

where V is the driving voltage for the modulator and f is

Manuscript received XXXXX. This work was supported in part by the Office of Naval Research and the NASA Earth Science Technology Office.

W. S. Rabinovich, R. Mahon and P. Goetz are with Code 5650, US Naval Research Laboratory, Washington, DC 20375 USA (email: Rabinovich@nrl.navy.mil)

D. S. Katzer and S. Binari are with Code 6850, US Naval Research Laboratory, Washington, DC 20375 USA

E. Waluschka is with NASA Goddard Space Flight Center, Greenbelt, MD 20 USA

G. C. Gilbreath is with Code 7210 with Code 5654, US Naval Research Laboratory, Washington, DC 20375 USA

the modulation rate. This power consumption can become large for high data rates and the heating it induces in the MQW may distort the retro-reflected beam ruining the link.

III. Cat's eye modulating retro-reflector

Optimizing an MQW MRR link requires simultaneously increasing the optical aperture while decreasing the MQW size. This cannot be achieved with a corner cube based retro-reflector since the modulator must cover the optical aperture. Corner cubes, however, are not the only kind of passive retro-reflector. Cat's eye retro-reflectors have been used for many years particularly in interferometry. Unlike corner cubes there is no one form of cat's eye but all incorporate focusing optics either in reflective or transmissive form or both. Using a cat's eye retro-reflector it is possible to decouple the size of the retro-reflector optical aperture from the size of the modulator by placing the modulator at the focus. However, because the focal spot will move as the relative angle between the interrogator and the MRR changes, the required size of the MQW is now coupled to the field of view (FOV) of the MRR. We define the FOV of the cat’s eye MRR as the full field of input angles over which the modulated retro-reflected signal power is at least half of the value at normal incidence

The classic form of a cat's eye retro-reflector incorporates a ball lens and a hemispherical reflector. This sort of cat's eye is not optimal for two reasons. First, it has a high amount of spherical aberration resulting in a large beam divergence for the retro-reflected signal. Second, it has a curved focal plane, not well suited to the planar MQW. Instead we have used an alternative design, coupling a two-element telecentric lens, with a 1 cm effective aperture and 3 cm focal length, and a flat reflector in the focal plane. The telecentric condition assure retro-reflection. The optical system is shown in Figure 1.

Such a retro-reflector is not diffraction-limited. We measured the retro-reflected beam divergence of the cat's eye at normal incidence and found that it was 1 milliradian, approximately 4 times the diffraction limit for a 1 cm aperture. Thus in comparing this kind of MRR to a corner-cube one must take into account the fact that the retro-reflected beam from the cat’s eye will diverge more for the same aperture, reducing the power received at the interrogator. Because of this, for long-range links, the 1 cm diameter cat's eye MRR has an effective diameter of 5 mm, returning the same amount of light as a corner cube MRR of this diameter.

The FOV of a cat's eye MRR is set by the optical FOV of the retro-reflector and the size of the modulator. The optical FOV of the cat's eye depends on any vignetting in the cat's eye and distortions in the retro-reflected beam that increase its divergence and decrease the power returned to the interrogator. For short ranges where the retro-reflected beam is smaller than the receive optics of the interrogator only the vignetting matters, but for longer ranges both these effects must be convolved. Figure 2 shows the vignetting and combined vignetting and distortion loss measured for the cat's eye as a function of angle. For a short-range link the MRR has a half power FOV of about 30 degrees, while for longer range, where the combined curve is used, the FOV is about 20 degrees.

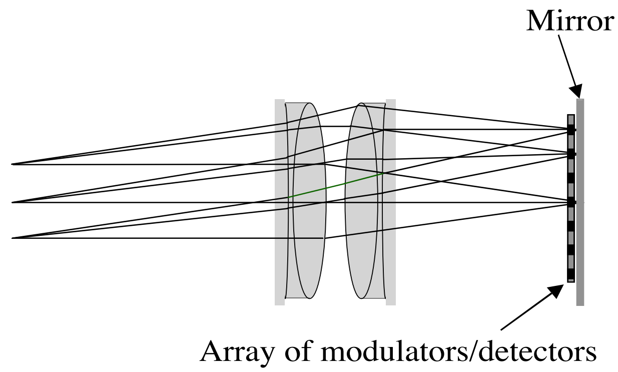

Fig. 1. Cat’s eye modulating retro-reflector using a telecentric lens pair and a pixellated MQW modulator in the focal plane. Different input angles focus on different pixels of the MQW array.

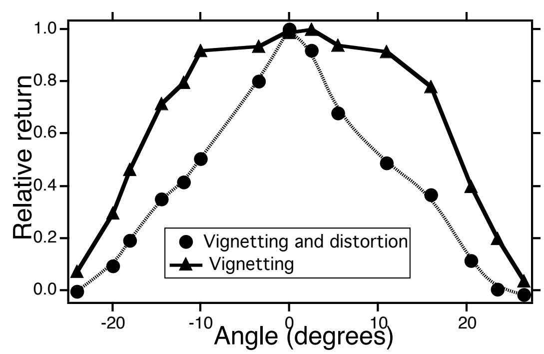

Fig. 2. Relative return of the cat's eye retro-reflector as a function of incident angle considering the effects of both vignetting and combined vignetting and distortion.

The limits that the size of the MQW modulator place on the FOV are determined by the motion of the focal spot with incident angle. We measured the size of the cat's eye's focal spot as 140 microns for normally incident light. The spot moves 0.4 mm per degree as the angle of incidence varies.

To examine the performance of the device as a modulating retro-reflector we placed a sparse linear array of MQW modulator pixels at the focal plane of the cat's eye. The array consisted of three 1 mm diameter MQW pixels with a center-to-center separation of 2.5 mm. The array thus covered a discontinuous FOV of 12.5° x 2.5° with a field of view of 2.5° x 2.5° for each pixel. Such an array may be useful when several interrogators dispersed over a wide field simultaneously illuminate the cat’s eye.

The MQW used consisted of 75 periods of 8.5 nm $In_{0.17}Ga_{0.83}As$ wells separated by 3.4 nm $Al_{0.13}Ga_{0.87}As$ barriers. It was grown via molecular beam epitaxy on a GaAs substrate. The exciton resonance for this structure falls at 980 nm, a wavelength at which the GaAs substrate is transparent. This allowed us to place the MQW in front of a flat mirror. Alternatively we could deposit a reflective coating of the wafer itself.

The modulator has a double-pass extinction ratio of 0.6 with 15 V driving voltage and an optical bandwidth of approximately 10 nm. It is possible to achieve extinction ratios as high as 0.3 with alternative MQW designs. The layer structure for this design was chosen with thin barriers to allow the MQW to act as both a modulator and a photodetector, at the cost of reduced extinction. The MQW exhibits a responsivity of 0.3 A/W when used as a photodetector.

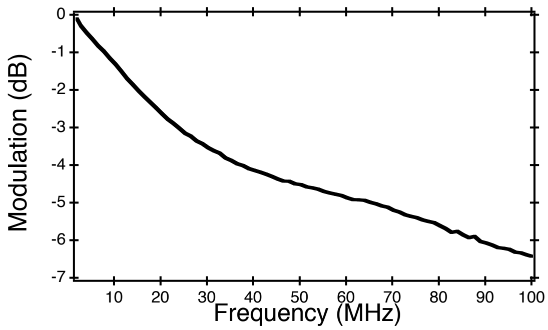

Figure 3 Modulation response of a 1mm diameter MQW pixel as a function of frequency

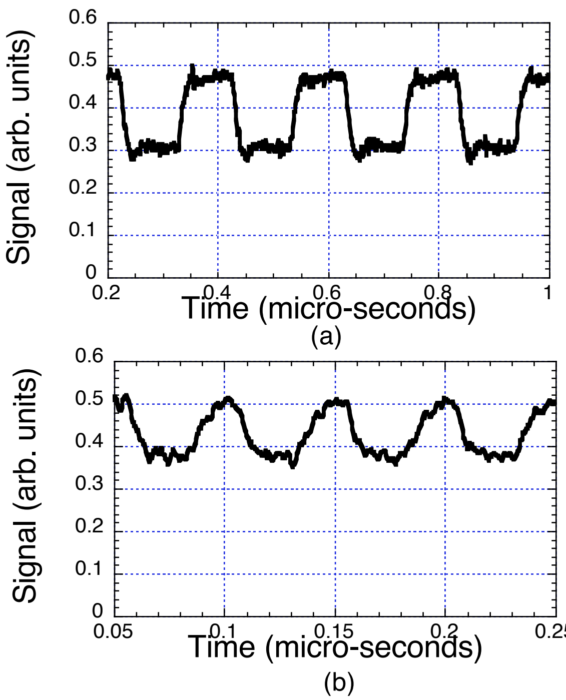

Fig. 4 Retro-modulated signal from cat's eye device with square wave signal at (a) 10 Mbps and (b) 40 Mbps.

The frequency response of one of the MQW modulator pixels is shown in Fig. 3. The 3 dB.point of the modulation is at 25 MHz.

The retro-modulated signal from the cat's eye is shown in Fig. 4a at a data rate of 10 Mbps and in Fig. 4b at 40 Mbps. At the higher date rate, the RC time limit of the device becomes observable and the extinction ratio declines to 0.7. If all 3 pixels in the modulator array are driven in parallel with the same signal the cat's eye MRR draws 30 milliwatts of electrical power at 10 Mbps and 120 milliwatts at 40 Mbps. An equivalent corner-cube modulator, pixellated to allow these data rates, would draw 0.25 Watts at 10 Mbps and 1 Watt at 40 Mbps.

IV. Conclusion

Cat's eye modulating retro-reflectors can allow much higher data rates at lower power consumption than corner cube based MRR. In both kinds of MRR the limitation of RC time constant can be circumvented by pixellization. The principle difference in the present design is that the total area of the modulator array can be smaller for the cat's eye, depending on FOV. As the FOV increases the advantage of this cat's eye decreases. For a fully filled FOV of 12.5° the size of the cat's eye MQW must be 5 mm, the same as for an equivalent corner cube MRR. Thus for an FOV greater than 12.5° there is no power consumption advantage for this cat's eye MRR over the corner cube MRR. Nonetheless there are many applications for which a system with a FOV less than 10° is not a handicap. In addition in other applications only selected parts of a large FOV may need to be filled in so that a sparse array of MQW pixels may be appropriate.

A more sophisticated optical design could increase the FOV over which the cat's eye is advantageous either by providing a diffraction limited return or by reducing the f-number of the cat's eye. However, an alternative approach exists that could provide much larger performance gains. Because the focal spot in the cat's eye is small, only a portion of the MQW is illuminated at any given time. As the relative angle between the interrogator and MRR changes the illuminated portion of the modulator also changes, but these changes take place slowly. If the MQW modulator is a pixellated array we can take advantage of the photosensitivity of the MQW. By monitoring the photocurrent in each pixel in the MQW array the illuminated pixel can be determined. Then, only that pixel needs to driven with the modulation signal, greatly reducing power consumption. Such a system could use an array of sub-millimeter pixels and close links with data rates in the range of hundreds of Mbps over many kilometers.

We plan to study such switched cat's eye MRR in future work.

References

1 G. Nykolak, P. F. Szajowski, G. Tourgee and H. Presby, "2.5 Gbits/sec free space optical link over 4.4 km", Electr. Lett., pp. 578-579, April 1999.
2 Charles M. Swenson, Clark A. Steed, Imelda A. A. DeLaRue, and Robert Q. Fugate, "Low power FLC-Based Retromodulator Communications System", SPIE Proceedings 2990, pp. 296-310 (1997)
3 D. Pedersen and O. Solgaard, "Free space communications link using a grating light modulator", Sensors and Actuators A, 83, pp. 6-10, 2000.
4 G.C. Gilbreath, W.S. Rabinovich, T.J. Meehan, M.J. Vilcheck, R. Mahon, R. Burris, M. Ferraro, I. Solkolsky, J.A. Vasquez, C.S. Bovais, K. Cochrell, K.C. Goins, R. Barbehenn, D.S. Katzer, K. Ikossi-Anastasiou, M.J. Montes," Large-aperture multiple quantum well modulating retroreflector for free-space optical data transfer on unmanned aerial vehicles", Opt. Eng. 40: pp. 1348-1356, July 2001